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Evidence for curvilinear interpolation from dot alignment judgements

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Abstract

Visual interpolation between dots responsible for rectilinear versus curvilinear contour interpretation was examined with the psychophysical forced directional response (FDR) paradigm. Regular four-dot polygon segments, together with a target dot, were presented to the subjects for 150 ms. Subjects were required to indicate the direction of deviation of the target dot from the midpoint of the intermediate line segment. Crucial variables were the outer angle of the line segments and symmetry axis orientation of the polygon segment. Logistic regression analyses showed that curvilinear interpolation occurred for angles up to 30°, but emerged more pervasively under the vertical symmetry axis orientation for angles up to 60°.

Keywords: Visual interpolation; Contour perception; Good continuation

1. Introduction

When Wertheimer (1921), Wertheimer (1923; see Ellis, 1938; Beardslee & Wertheimer, 1958, for synoptic translations of the original German articles) formulated the main ideas and principles of Gestalt theory, he demonstrated this new approach to visual perception with stimuli consisting of dot configurations. The choice for those stimuli was elegant, since they present prototypical test cases for Von Helmholtz (1962) 'atomic sensory theory' (Hochberg, 1981, p. 259). The Gestalt theorists reacted against that type of theory by showing the inadequacy of the explanation of visual pattern perception in terms of additive and associative operations applied to elementaristic sensations. Dot configurations served to argue that relations between elements, rather than the elements themselves, carry the proper perceptual information, and that interactive, rather than additive perceptual operations account for perceived patterns.

Wertheimer's (1923) proposals of how pattern perception is governed by relational factors, like distance (Law of Proximity) and orientation between elements (Law of Good Continuation), became widely accepted as intuitively plausible. It took more than half a century, however, before attempts were undertaken to translate them into computational models of perceptual grouping by proximity and good continuation (e.g. Caelli & Umansky, 1976; Van Oeffelen & Vos, 1982, 1983; Zucker, 1984, 1986; Smits & Vos, 1986, 1987; Link & Zucker, 1987; Parent & Zucker, 1989; Zucker, Dobbins, & Iverson, 1989; Vos & Helsper, 1991; Compton & Logan, 1993; Kubovy & Wagemans, 1995; Feldman, 1996, 1997; Pizlo, Salach-Golyska, & Rosenfeld, 1997).

Still, several important questions with respect to the perception of dot configurations remain to be investigated. One of them, the topic of the present study, is concerned with a special case of Wertheimer's (1923) Law of Good Continuation, that is, in what way the visual system interpolates a (virtual) trajectory between neighbouring dots in the visual field. Following Link and Zucker's (1987) distinction of orientation perception in a single contour pattern — a crease — and in

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a multiple contour pattern — hair — we are here concerned with visual interpolation in one-dimensional (dotted) contours. In contrast, the studies of Zucker and his associates focused on multiple contour patterns.

The phenomenological facts of single contour patterns are deceivingly simple, as was demonstrated by the Gestalt theorist Koffka (1931) (Fig. 1). If a configuration of N dots is constructed such that each dot is positioned at the edge of a regular polygon, then, depending on N, either a rectilinear or a curvilinear contour is perceptually interpolated between adjacent dots. Koffka guessed that interpolation is curvilinear for $N \geq 8$, corresponding to an (outer) angle α of at most $360/8 = 45°$ of the polygon. Bouma (1976) stated that the mechanisms of interpolation for such configurations are still unclear, waiting for more experimental data. More conservatively than Koffka, he speculated $N = 10$ (36°) to constitute the transition point between rectilinear and curvilinear interpolation.

The goal of the present study surpasses the solution of the Koffka-Bouma controversy. Specifically, we aim to obtain a better insight in the objective determinants of angular versus curvilinear interpolation of one-dimensional contour patterns. In doing so, we want to circumvent the disadvantages of traditional, template matching and categorisation methods. These methods require a subject to tell whether a dot configuration looks angular or curved (e.g. Smits & Vos, 1987) or belongs to a particular category of 1-dimensional or 2-dimensional objects (e.g. Link & Zucker, 1987; Feldman, 1996, 1997). Before discussing the principals of the experimental tasks and the theoretical underpinnings of our new response paradigm, some theoretical and methodological objections to the traditional methods are raised.

A serious problem of the traditional methods is that, because of the arbitrariness of the responses 'curvilinear' and 'angular' in view of dot patterns, response selection is inevitably based upon cognitive considerations, next to perceptual arguments. The observer knows that strictly speaking none of the response alternatives is correct or wrong. Therefore, (s)he may directly derive the response from knowledge of additional constraints, like the range of variation in the order of dot polygons (number of dots) in an experiment. Additionally, low-order polygons, triangles, squares, ..., octagons, are overlearned angular patterns, whence responses to them are predictable for other reasons

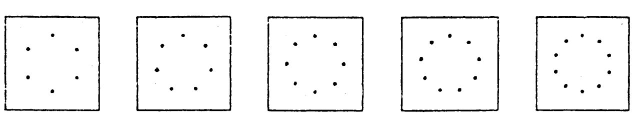

Fig. 1. Examples of regular dot patterns. From left (hexagon) to right (decagon) the perceptual interpretation changes from angular to circular.

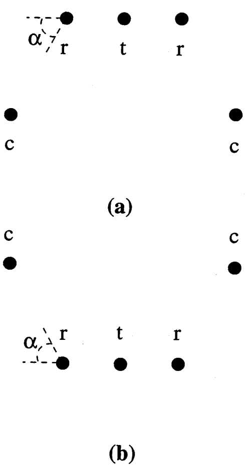

Fig. 2. Two examples of the stimuli used in the present study. t: target dot; r: reference dots; c: context dots; α: outer angle of the polygon segment c-r-r, varied over stimuli. (a) Orientation of the stimulus, referred to as 'up'; (b) orientation of the stimulus, referred to as 'down'. Both figures illustrate stimuli with a horizontal alignment (vertical axis of symmetry).

than bottom-up interpolation. Similarly, some higher-order polygons are well known (like the dodecagonal emblem of the European community), which may influence their perceptual interpretation.

Another problem, associated with the use of dot polygons as experimental stimuli, is the fact that variation of the order of dot polygons is necessarily correlated with either inter-dot distances (when stimulus size is kept fixed over stimuli), or with stimulus size (when one wants to fix inter-dot distances). These confoundings make it hard if not impossible to come up with unambiguous interpretations of experimental data.

The present study re-examines the shape of inter-dot interpolation in three experiments[1], using tasks and stimuli which meet none of the objections mentioned so far. In contrast to traditional methods, the tasks used in our experiments are genuine perceptual ones. They require a subject to judge whether a central dot is above/below two neighbouring dots, or to the left/right of two such dots. The central dot is called the target, the neighbours reference dots. One of the experimental manipulations is the addition of two so called context dots, positioned in such a way that the reference dots and the context dots together constitute a segment of a regular polygon (Fig. 2). Using four-dot segments as stimuli the outer angle α, in Fig. 2, or the order of the polygon, can be varied, while stimulus size (approximately) and interdot distance are kept constant over the stimuli. It is observed that the four-dot stimuli in

[1] However, a fourth experiment was performed but since it served only a methodological purpose, the effect of a blocked design (Experiment 1–3) versus a mixed design (Experiment 4), and because its results left the conclusions of Experiments 1–3 unchanged, Experiment 4 will only be dealt with in Section 5.

question are endowed with bilateral symmetry, the axis of symmetry is on the alignment of the reference dots.

We hypothesise that the context dots induce bias in the above/below and left/right judgements, *even if these dots are irrelevant for the task completion*. Consider for example Fig. 2a. If the subject interpolates a curvilinear trajectory through the four dots, the target, when positioned exactly in the middle of the virtual straight line between the reference dots, is positioned below the curvilinear trajectory. For the polygon segment in Fig. 2b, curvilinear interpolation, given the same position of the target, implies that the target is positioned above the curvilinear trajectory. Hence, a larger proportion of 'below' responses for stimulus orientation 'up' (Fig. 2a) and a larger proportion of 'above' responses for orientation 'down' (Fig. 2b) is indirect evidence for curvilinear interpolation for the stimuli in Fig. 2. A larger proportion of 'left' responses for the 'right' orientation (rotate Fig. 2a 90° clockwise) and a larger proportion of 'right' responses for the 'left' orientation (rotate Fig. 2b 90° clockwise) will furnish similar evidence for curvilinear stimulus interpolation.

Conventional signal detection paradigms as discussed in standard texts of detection theory (e.g. Green & Swets, 1966; Macmillan & Creelman, 1991) require a subject to report whether or not (s)he perceived a deviation (change/difference), without the need to specify its direction. Since we are not primarily interested in whether a deviation of the target is or is not detected, but in the direction of perceived deviation, the conventional paradigms do not suit our aim. Therefore, another paradigm is chosen, called the forced directional response (FDR) paradigm. The name refers to the fact that the subject is not allowed to produce a 'no change (deviation in this case)' response. The FDR paradigm requires the subject to report the *direction* of a deviation in a stimulus, whereby the latter one is in one of two different possible opposite directions. The paradigm has recently successfully been introduced in the area of auditory pattern perception (Vos, Van Assen & Franek, 1997). While the deviation in the auditory stimuli of the latter study consisted of an acceleration versus a deceleration of tempo in a short tone series, the deviation in the stimuli of the present study will have a similar, albeit static constraint ('up/down' or 'left/right') of the target. Application of the FDR tasks is then expected to result in a greater response bias for the response 'above' for stimuli represented by Fig. 2b than for stimuli represented by Fig. 2a. Thus, by varying the angle α over conditions, we may use the difference in response bias as indirect evidence for curvilinear interpolation as a function of angle α.

In Experiment 1, the reference dots are presented horizontally in the visual field (vertical axis of symmetry), and in Experiment 2 vertically (horizontal axis of symmetry). In both experiments, the target is either displaced off the virtual line between the reference dots but preserving equal distance to both reference dots, the experimental condition henceforth called OFF-LINE task, or it is displaced on the virtual line away from its midpoint, a control condition called ON-LINE task. The two experimental manipulations are on: (1) the orientation of the polygon segment: 'up' or 'down' in Experiment 1; and 'left' or 'right' in Experiment 2; and (2) the angle, with three levels in Experiments 1 and 2: 30, 45, and 90°, together with a control condition in which no context dots are presented at all, denoted by 'no-context'. In Experiment 3, both types of orientation of the reference dots are introduced under the OFF-LINE task only, but this time with other levels of the angle, namely 0, 15, 60, and 75°.

2. Experiment 1

In Experiment 1, the stimuli were presented under the condition of a horizontal alignment of the reference dots. In the control tasks (detecting a deviation direction in ON-LINE stimuli), no differences in response bias for orientations 'up' and 'down' are expected. The same holds for the control stimuli in the OFF-LINE task where no context dots were present. However, it is expected that, due to curvilinear interpolation, at least for some angles α, a difference in response bias will be observed. Values of α were chosen such that: (1) curvilinear interpolation is expected to occur ($\alpha = 30°$); (2) rectilinear interpolation is expected to occur ($\alpha = 90°$); and (3) a more definite answer can be given with respect to the discordance of Koffka's and Bouma's guess about the transition point between both types of interpolation ($\alpha = 45°$).

2.1. Method

2.1.1. Subjects

Eight students of the Nijmegen University took part in the experiment and either were paid or given curriculum credits for their participation. They were naive with respect to the goal of the experiment. Each of them had normal or corrected to normal vision.

2.1.2. Apparatus and stimuli

Instruction and stimulus presentation were mediated by a DOS computer controlled Philips Brilliance 15 in. colour monitor. Stimuli were displayed in 600∗480 VGA mode, refresh rate 60 Hz, and were presented within the circular aperture, radius 95 mm, of a black card that completely covered the monitor's frame. The subject was seated at a distance of approximately 90 cm in front of the gravitationally vertically (90°) adjusted monitor. Prior to an experimental session, it was ensured, with the help of an adjustable chair and a chin rest, that the participant's eyes were subjectively aligned with the monitor's horizontal and vertical meridians. The experimental room was darkened in order to suppress the possible influence of more remote spatial reference cues during the experiment.

The stimuli were presented such that the midpoint of the reference dots was positioned in the centre of the screen. The distance between the reference dots and between a reference dot and the neighbouring context dot was 100 pixels, which corresponded to a metric distance of approximately 40 mm (visual angle of 2.55°). Stimuli differed in: orientation ('up', see Fig. 2a, and 'down', see Fig. 2b); angle (90, 45, 30°, and a control condition in which no context dots were presented); and deviation of the target. Over trials, the target was positioned at -3, -2, -1, 0, 1, 2, 3 pixels (visual angle from 0.025 to 0.076°) above the midpoint between the reference dots in the OFF-LINE tasks, and at the same distances to the left of that midpoint in the ON-LINE tasks. In that way, the positioning of the target took place in steps of 0.4 mm from the midpoint, and in steps of 2% of the distance from midpoint to reference dot.

2.1.3. Procedure

Subjects were tested individually. OFF-LINE and ON-LINE tasks were examined in two parts, separated by a mandatory pause of 15 min. Each part consisted of two series differing in orientation, each series consisting of four blocks. Stimuli in each block were similar with respect to level of the angle. Prior to the presentation of a block, the subject received an extensive instruction of the task at hand. The instruction required the subject to indicate by means of the arrow keys whether the target was positioned up/down (OFF-LINE task) or to the left/right (ON-LINE task) of the midpoint of the reference dots. The instruction was followed by a number of practice trials. First, two control stimuli with extreme positioning of the target (deviation of -6% and $+6\%$) were shown. Subsequently, it was explained to the subject that four different types of stimuli were going to be presented, differing in the number and the position of dots irrelevant to the task. They were explicitly told that only the three dots in the middle of the screen were important for the task. Then, four easy experimental stimuli (deviation $\pm 6\%$) were presented without presentation duration restrictions. At the end of the general instruction, the subject was advised to pause regularly, and to blink with the eyes whenever fatigue was felt.

The block instructions were exactly the same for all blocks. First, they were told that not all stimuli were easy, and this was illustrated with four representative stimuli (deviations of $\pm 6\%$ and of $\pm 2\%$, respectively). The subjects were not informed that the tasks contained stimuli where the target was exactly in the midpoint of the reference dots. Finally, it was specified (and illustrated with seven practice trials, each with a different deviation of the target) that the task was made additionally difficult by restriction of the stimulus inspection time.

A trial was initiated by pressing the spacebar. After a delay of 200 ms, the stimulus was shown for 150 ms, whereafter the subject had to press one of the two relevant arrow keys. After the response, followed by another delay of 200 ms, the next trial could be triggered in a similar way.

2.1.4. Design

Four subjects started with the OFF-LINE task, the others with the ON-LINE task. Half of each group first received the 'down' orientation. For each subject, the order of presentation of angle × orientation × task conditions constituted a Latin square design, such that each angle condition was preceded and followed by another angle condition only once. Each subject received a different Latin square design. Within each of the 4∗2∗2 blocks, each of the seven stimuli was presented 15 times, whereby the order of stimuli within a block was randomised. Thus, each subject produced 1680 responses in total.

2.2. Results and conclusions

Responses were coded as '1' for a response 'above' in the OFF-LINE task and for a response 'left' in the ON-LINE task. The opposite responses were coded as '0'. Since traditional methods like ANOVA are not appropriate for the data analysis of binary responses, logistic regression was applied, a technique designed for the analysis of data with a binary dependent variable (see, e.g. Hosmer & Lemeshow, 1989 and Kleinbaum, 1994, for a detailed treatment of logistic regression analysis). An additional reason to apply logistic regression was that the logistic function is the psychometric function in a detection task following Luce's Choice Theory (Luce, 1959, 1963). In logistic regression, the proportion '1' in the data is predicted by

$$P_{\text{pred}} = \frac{e^{g(x)}}{1 + e^{g(x)}} \tag{1}$$

where P_{pred} and $g(x)$ denote, respectively, the predicted proportion and a linear combination of the variables x in the experiment. The linear function $g(x)$ is obtained by the so-called logit transformation on P_{pred}.

$$g(x) = \ln \frac{P_{\text{pred}}}{1 - P_{\text{pred}}} \tag{2}$$

In all subsequent analyses, models are discussed in terms of the logit $g(x)$, because of its close relationship to the well known linear regression model.

Table 1
Summary table of results of logistic regression models[a]

Model for $g(D, O, \alpha)$		OFF-LINE	ON-LINE
Model I:	$\gamma+\beta D$	$\chi^2_{(2)}=4781.91$ (<0.0001)	$\chi^2_{(2)}=2968.76$ (<0.0001)
	Bias	$\chi^2_{(1)}=9.60$ (0.0019)	$\chi^2_{(1)}=17.41$ (<0.0001)
	Deviation	$\chi^2_{(1)}=4759.00$ (<0.0001)	$\chi^2_{(1)}=2940.37$ (<0.0001)
Model II:	$\gamma_\alpha+\beta_\alpha D$	$\chi^2_{(6)}=22.33$ (0.0011)	$\chi^2_{(6)}=19.11$ (0.0040)
	Angle*bias	$\chi^2_{(3)}=5.52$ (0.1372)	$\chi^2_{(3)}=3.70$ (0.2957)
	Angle*deviation	$\chi^2_{(3)}=18.46$ (0.0004)	$\chi^2_{(3)}=15.27$ (0.0016)
Model III:	$\gamma_\alpha+\beta_\alpha \mathrm{D}+\omega O$ Orientation	$\chi^2_{(1)}=103.14$ (<0.0001)	$\chi^2_{(1)}=0.01$ (0.9164)
Model IV:	$\gamma_\alpha+\beta_\alpha \mathrm{D}+\omega_\alpha O$ Angle*orientation	$\chi^2_{(3)}=41.22$ (<0.0001)	$\chi^2_{(3)}=8.88$ (0.0309)
Model V:	$\gamma_\alpha+\beta_{\alpha \mathrm{O}}\mathrm{D}+\omega_\alpha O$ Angle*deviation*orientation	$\chi^2_{(4)}=2.22$ (0.6954)	$\chi^2_{(4)}=2.25$ (0.6899)

[a] Subsequent rows embody increasingly complex models for explaining the data. A cell in a row contains the improvement of fit as a result of adding the variables to the explanation described in that row. Both the improvement by individual variables alone and by the variables combined are presented, together with their degrees of freedom and significance.

As a first step of the analyses, the data were analysed separately for each subject. Examining the proportion of ones for each orientation*angle condition, it was found that two subjects apparently did not adhere to the task instructions. One of them answered randomly in one of the experimental blocks of the ON-LINE task and the other seemed to respond 'left' when the deviation was to the right and the other way around in one block of the ON-LINE task. Because those data were distorted, they were discarded and two new subjects were selected. No peculiarities were found in the data of the latter subjects.

A few individual response biases, that is, proportions (averaged over orientation and angle conditions) significantly different from 0.5, were found. In the OFF-LINE task, three proportions were larger than 0.5, but less than 0.6, and in the ON-LINE task, two were larger than 0.5 and one less, but all five of them were in the interval (0.46, 0.57). We assume that the small but significant differences in overall response bias reflected individual differences in preference for one of the two responses. It must be noted, however, that the different overall response biases do not have negative side-effects on the testing of our hypotheses, because they are formulated in terms of the difference in response bias for the two stimulus orientations, which is independent from the overall response bias itself.

Logistic regression analysis applied to the individual data sets showed that, apart from the overall response biases, in general no large systematic differences existed between the data sets. Therefore, only the results of the logistic regression analyses on the grouped data will be reported[2]. Because ten tests of interest were conducted on the data set of the present experiment as well as on the data of the subsequent experiments, a significance level of $0.05/10=0.005$ was chosen. The statistical power of the tests is high, even for such a conservative significance level, in view of the massive number of data points (13440).

The results of the analyses of relevant and increasingly complex models are summarised in Table 1, which is similar to an ANOVA summary table.

A model in a specific row incorporates the independent variables of the models in the row(s) above and includes one (in case of Models III, IV, and V) or two (Models I and II) other variables. For example, Model II incorporates the main effects of deviation and bias, plus the interaction effects angle*bias and angle*deviation, of which the significance is reported in columns two (OFF-LINE) and three (ON-LINE). The first row in Table 1 (Model I) reports the improvement of fit in comparison to the trivial base model $g(D, O, \alpha)=0$ (implying a predicted proportion of 0.5 for all conditions) by adding bias and deviation to it.

Improvements in fit in logistic regression are measured by the likelihood ratio (LR) test statistic. The LR test statistic is approximately distributed as a chi-square with degrees of freedom (*df*) equal to the number of parameters added to the model. Cells in Table 1 report the chi-squares, their *df*, and their P-values.

Model IV in Table 1, appropriate to test our hypothesis on the effects of angle on curvilinear interpolation, is formulated as

$$g(D, O, \alpha)=\gamma_\alpha+\beta_\alpha D+\omega_\alpha O$$

for $\alpha=30$, 45, 90 and 'no-context'. D symbolises variable deviation ($-6\%, \ldots, 6\%$), and O is a dummy variable, denoting orientation 'up' when $O=0$ under

[2] Logistic regression analysis applied to the aggregate data including eight response bias parameters, one for each subject, yielded P-levels for the independent variables of interest that did not differ more than 10% of the P-levels reported here. This is also true for Experiments 2 and 3. We therefore are confident that the results on the aggregate data reported in the amnuscript reflect the true effects of the independent variables.

the OFF-LINE task, and orientation 'down' if $O=1$. Symbol α represents the index for the variable angle. Parameters β_α typify for each level of angle the effect of deviation on the logit of the response 'above', or, in other words, the interaction angle∗deviation. The interpretation of the other parameters is obtained by substituting the values of dummy O. Parameters γ_α represent for each of the four angles the response bias for response 'above' for orientation 'up' ($O=0$). By substituting $O=1$, the response bias for orientation 'down', equal to $\gamma_\alpha+\omega_{\alpha,}$ is obtained for all angles. Hence, parameters ω_α represent the difference in response bias for the two orientations for each angle, in other words, the interaction angle∗orientation, and for that reason are crucial for testing our hypothesis.

Model III, with only one parameter for the orientation effect on curvilinear interpolation averaged over angle, is also relevant for testing our hypothesis: if the improvement of Model IV over the latter model is larger than a critical value, then the interaction angle∗orientation is significant and the curvilinear interpolation hypothesis may be confirmed.

Starting with the OFF-LINE results, a highly significant effect of orientation was found (Model III, $\chi^2(1)=103.14$, $P<0.0001$), and the extent of this effect varied over angle (Model IV, $\chi^2(3)=41.22$, $P<0.001$). The estimated values of ω_α and their significance levels are presented in Table 2, column 1.

As expected, there was a significant effect ($P<0.0001$) of orientation for $\alpha=30$, but not for $\alpha=90$. The fact that the orientation effect for $\alpha=45$ was also significant, confirmed Koffka's (1931) guess. Hence, although the context dots were to be neglected during task completion, they caused the subjects to interpolate a curvilinear trajectory through the dots for angles of 30 and 45°, resulting in different response biases for the orientations 'up' and 'down'. The sizes of the effects are apparent from Fig. 3, which depicts both the predicted and the observed proportions for all angles. When the target was in the middle of the reference dots ($D=0$), the difference in the proportion of responses 'above' was approximately 0.30 (Fig. 3b and c). Although the effect for $\alpha=45$ was larger than for $\alpha=30$, the difference between the two effects was not significant (one-tailed Wald-test, $P=0.0864$).

Table 2
Parameter estimates and their significance for the effect of orientation per angle (ω_α) for both the OFF-LINE and ON-LINE task[a]

Angle	Parameter ω_α (significance)	
	OFF-LINE	ON-LINE
'No-context'	+0.2170 (0.1752)	−0.1805 (0.1335)
90	+0.3321 (0.0318)	−0.1475 (0.2497)
45	+1.4105 (**0.0000**)	+0.0844 (0.5160)
30	+1.1016 (**0.0000**)	+0.2716 (0.0275)

[a] Significance levels smaller than 0.005 are bold-faced.

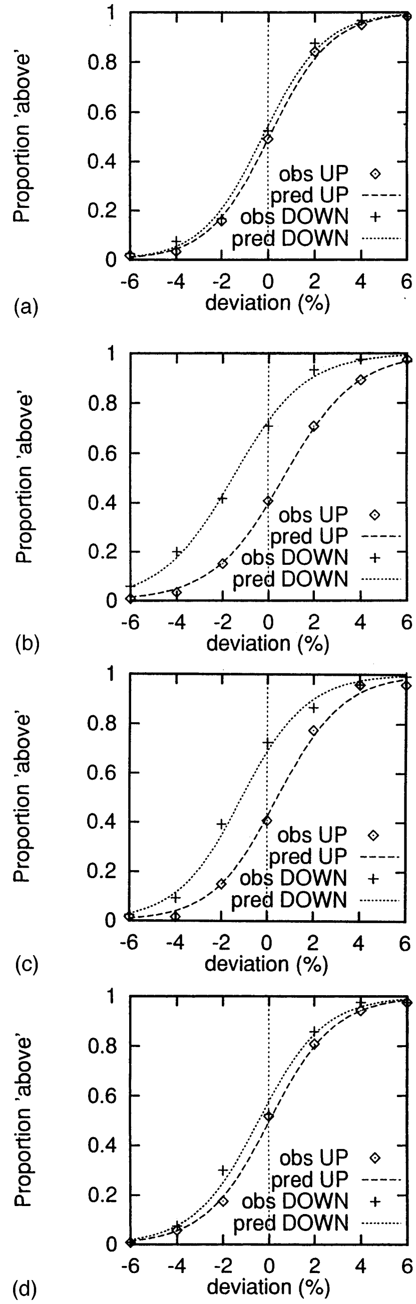

Fig. 3. Experiment 1: OFF-LINE task for horizontally aligned stimuli. Observed and predicted proportion of responses 'above' as a function of deviation percentage of the target dot from the midpoint for Orientation 'up' and 'down' for the OFF-LINE task in Experiment 1. (a), (b), (c), (d) represent respectively, the observed and predicted proportions of stimulus condition 'no-context' and angle 30, 45, and 90°.

Table 1 further shows that the response bias for response 'above' (Model I, $P<0.0001$) was significantly different from 0.5, but did not vary over the angle (Model II, $P=0.1372$). The interaction angle∗deviation was significant, however (Model II, $P=0.004$), with the largest effect when no context dots were presented. The results of Model V showed that there was no angle∗deviation∗orientation interaction. This justifies the presentation of Model IV as our final model of the OFF-LINE task.

Turning to the ON-LINE data, the hypotheses were confirmed: (i) there was no general effect of orientation (Table 1, Model III, $P=0.9164$); (ii) the interaction angle∗orientation was not significant (Table 1, Model IV, $P=0.0309$), and Table 2 shows that none of the individual parameters were significant. It is therefore concluded that the position of the context dots had no effect on the bias to respond 'left' in the control task.

As for the OFF-LINE task, the response bias (for response 'left') was significantly different from 0.5 (Model II, $P<0.0001$) but constant over all angles (Model II, $P=0.2957$). The interaction angle∗deviation was again significant (Model II, $P=0.0016$), but, in contrast to the OFF-LINE results, the effect of deviation for angle condition 'no-context' was smallest. Finally, Model IV could not be improved by including interaction angle∗deviation∗orientation (Model V, $P=0.6899$).

In addition to the major findings reported so far, a striking difference in accuracy, that is differential sensitivity as measured by the effect of deviation, has to be discussed. Specifically, subjects' accuracy was considerably higher for the OFF-LINE task. The latter fact agreed with the retrospective comments of subjects: the ON-LINE task was judged as much more difficult. The difference in accuracy is apparent from Fig. 4, which portrays Model I with two parameters, one for bias and one for deviation, for each task separately.

The difference between the two deviation parameters β was highly significant ($\chi^2(1)=208.44$, $P<0.0001$), which indeed shows that difference in accuracy was much higher in the OFF-LINE task. Interpretations of the accuracy difference are delayed until Section 5.

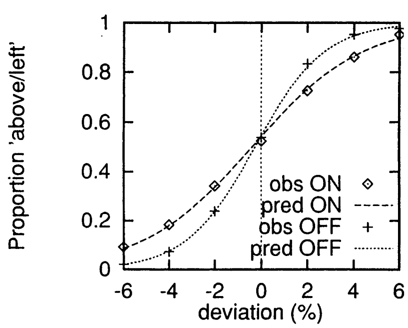

Fig. 4. Experiment 1: comparison of OFF-LINE and ON-LINE task for horizontally aligned stimuli. Observed and predicted proportions responses 'above' as a function of deviation percentage of the target dot from the midpoint for both the OFF-LINE and ON-LINE task in Experiment 1, averaged over all orientation and angle conditions.

3. Experiment 2

The findings of Experiment 1 were obtained with experimental stimuli endowed with left-right symmetry, the axis passing orthogonally through the midpoint of the virtual line connecting the two reference dots. It is well known that vertically symmetrical patterns are more salient than those with a differently oriented axis of symmetry (e.g. Palmer & Hemenway, 1978; Barlow & Reeves, 1979; Bornstein & Styles-Davis, 1984; Zimmer, 1984; Wenderoth, 1994; Dakin & Hess, 1997; see Wagemans, 1995 for a review). It has been suggested that the origin may be sought in evolutionary advantages for ontogenetic and phylogenetic survival among vertebrates (Tyler, 1996). Consequently, the process of visual interpolation between symmetrically arranged dots might also be affected by the orientation of the symmetry axis. Therefore, it was decided to investigate the perception of the same stimuli as used in Experiment 1, but now presented with the opposite, horizontal axis of symmetry. The same results are expected as in Experiment 1: evidence for curvilinear perception in the OFF-LINE task for angle conditions 30 and 45°, but not so for the other angle conditions and in the ON-LINE task.

3.1. Method

The experimental set-up was exactly the same as in Experiment 1, except for the following modifications: (1) a new set of eight subjects was recruited from the same pool of students; (2) the stimuli were this time presented vertically under left and right orientation conditions.

3.2. Results and conclusions

Responses were coded as '1' for a response 'above' in the ON-LINE task, and for a response 'left' in the OFF-LINE tasks. As in Experiment 1, the data were analysed with logistic regression, starting with the individual data sets.

Four of the eight subjects seemed to respond randomly to stimuli in at least one of the 16 blocks. Their data were discarded and four new subjects completed the task. Again, two of them apparently did not adhere to the task instructions, wherefore they were replaced by two new subjects. All the peculiarities in the data occurred for the ON-LINE-task. The fact that more of them were found in the present experiment compared to Experiment 1 suggests that the ON-LINE task in a vertical alignment is more difficult than the same task in a horizontal alignment.

All individual proportions in the OFF-LINE task were in the interval (0.45, 0.50). However, the interval for the ON-LINE task was much larger: (0.31, 0.62).

Table 3
Summary table of results of logistic regression models[a]

Model for $g(D, O, \alpha)$		OFF-LINE	ON-LINE
Model I:	$\gamma+\beta D$	$\chi^2_{(2)}=4674.42$ (<0.0001)	$\chi^2_{(2)}=1999.03$ (<0.0001)
	Bias	$\chi^2_{(1)}=32.34$ (<0.0001)	$\chi^2_{(1)}=19.08$ (<0.0001)
	Deviation	$\chi^2_{(1)}=4630.17$ (<0.0001)	$\chi^2_{(1)}=1954.82$ (<0.0001)
Model II:	$\gamma_\alpha+\beta_\alpha D$	$\chi^2_{(6)}=12.11$ (0.0596)	$\chi^2_{(6)}=7.67$ (0.2633)
	Angle*bias	$\chi^2_{(3)}=10.84$ (0.0126)	$\chi^2_{(3)}=4.84$ (0.1839)
	Angle*deviation	$\chi^2_{(3)}=0.51$ (0.9167)	$\chi^2_{(3)}=2.44$ (0.4862)
Model III:	$\gamma_\alpha+\beta_\alpha D+\omega O$ Orientation	$\chi^2_{(1)}=0.40$ (0.5271)	$\chi^2_{(1)}=5.11$ (0.0237)
Model IV:	$\gamma_\alpha+\beta_\alpha D+\omega_\alpha O$ Angle*orientation	$\chi^2_{(3)}=13.83$ (0.0031)	$\chi^2_{(3)}=2.83$ (0.4185)
Model V:	$\gamma_\alpha+\beta_{\alpha O} D+\omega_\alpha O$ Angle*deviation*orientation	$\chi^2_{(4)}=2.96$ (0.5645)	$\chi^2_{(4)}=9.02$ (0.0606)

[a] Subsequent rows embody increasingly complex models for explaining the data. A cell in a row contains the improvement of fit as a result of adding the variables to the explanation described in that row. Both the improvement by individual variables alone and by the variables combined are presented, together with their degrees of freedom and significance.

Six of the proportions in the latter interval were significantly different from 0.5 ($P<0.005$), three of them smaller, and three of them larger. The larger variance in the individual response biases can obscure the measurement of the effects of interest if they are not incorporated in the model. Therefore, logistic regressions for the data of the ON-LINE task were run once including and another time excluding individual response bias parameters. Because the P-levels of the tests of effects ω_α did not differ much between the two analyses (see footnote 2), only analyses of models without individual parameters are reported. The models are principally the same as those considered in Experiment 1 and, accordingly, the interpretation and the discussion of the results shown in Table 3 and Table 4 run parallel to those in Experiment 1.

Concentrating first on the results of the OFF-LINE task, the incorporation of a main effect of orientation in Model III did not result in an improvement of fit. However, the angle*orientation interaction was significant. The tests for each of the four angles reported in Table 4 showed that the effect of $\alpha=30°$ was significant, conforming to the expectation, but that the effect of $\alpha=45°$ was not, contrary to what was found in Experiment 1. The significant effect for $\alpha=30°$ deserves caution however; it was significant for only one subject, and for the other subjects only emerged as a trend.

There were other differences in results between Experiment 2 and Experiment 1; as it can be seen in Fig. 5b, the effect for $\alpha=30°$ was much smaller than it was established in Experiment 1 (Fig. 3b).

The differences suggest that, for some reason, the visual system is more prone to curvilinear interpolation with respect to horizontally aligned than to vertically aligned stimuli. Possible interpretations of this asymmetry are delayed until Section 5, where all three experiments are discussed.

To finish the discussion of the results of the OFF-LINE task, Table 3 further shows that the average response bias was significantly different from 0.5, but effects angle*bias, angle*deviation (Model II), and the second order interaction (Model V) were not. Hence, Model IV provided an accurate and relatively simple description of the data.

No effects of orientation and of angle*orientation were expected for the ON-LINE task. Again, the hypotheses were confirmed; neither the main effect (Table 3, Model III) nor the four individual contrasts for angle (Table 4) were significant. Further inspection of Table 4 yields the conclusion that Model I, incorporating an average response bias and a general effect of deviation, is not improved by adding any of the first and second order interaction effects.

As in Experiment 1, the differences in the accurateness of the responses between the two types of task was remarkable. The difference is apparent from Fig. 6, which plots Model I for both tasks. Testing the difference in effect of deviation (β) indeed demonstrated that it was enormous ($\chi^2(1)=475.29$, $P<0.0001$). The parameter estimates and standard errors for the effect of deviation for the OFF-LINE and ON-LINE tasks were 1.3065 (0.0297) and 0.6286 (0.0164), respectively.

Table 4
Parameter estimates and their significance for the effect of orientation per angle (ω_α) for both the OFF-LINE and ON-LINE task[a]

Angle	Parameter ω_α (significance)	
	OFF-LINE	ON-LINE
'No-context'	+0.1205 (0.4159)	+0.1136 (0.3260)
90	−0.3375 (0.0228)	+0.2226 (0.0558)
45	+0.0113 (0.9402)	+0.2052 (0.0704)
30	+0.4410 (**0.0041**)	−0.0192 (0.8653)

[a] Significance levels smaller than 0.005 are bold-faced.

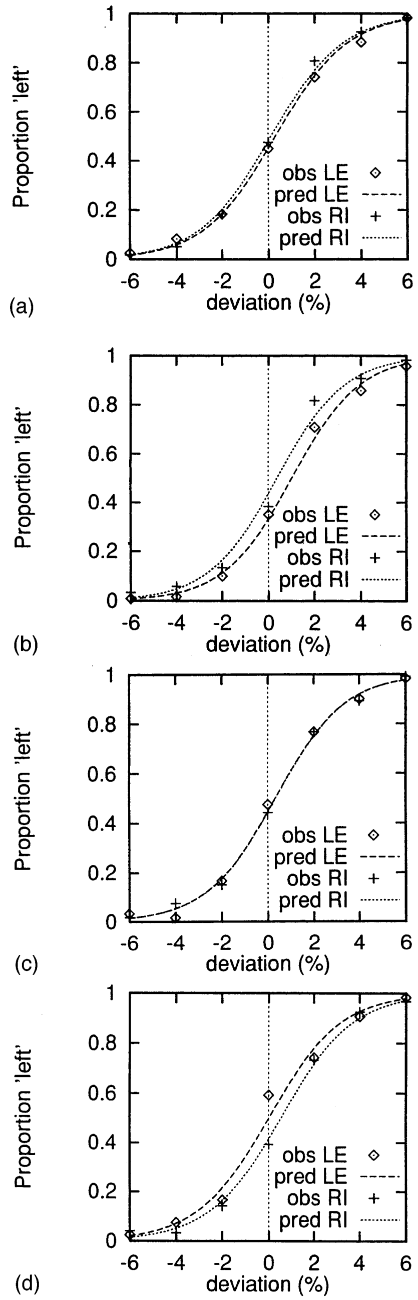

Fig. 5. Experiment 2: OFF-LINE task for vertically aligned stimuli. Observed and predicted proportions responses 'left' as a function of deviation percentage of the target dot from the midpoint for orientation 'left' and 'right' for the OFF-LINE task in Experiment 2. (a), (b), (c), (d), represent respectively, the observed and predicted proportions of stimulus condition 'no-context' and angle 30, 45, and 90°.

Comparing these estimates with those obtained in Experiment 1, 1.344 (0.0306) and 0.843 (0.0196), brings us to conclude that there was no difference in difficulty for the two OFF-LINE tasks, however, the ON-LINE condition in Experiment 2 was more difficult than in Experiment 1. The differences between Experiment 1 and 2 with respect to the results in the ON-LINE tasks will further be discussed in Section 5.

4. Experiment 3

In the two previous experiments, visual interpolation was examined for three angular conditions in the range of 0 and 90° (30, 45, and 90°, respectively). In order to get a more representative picture, it was decided to examine in Experiment 3 the three remaining 15° divisor conditions in the specified range, that is the conditions 15, 60, and 75°. Because both previous experiments had shown that, conforming to expectations, there were no effects of angle∗orientation in the ON-LINE task, it was decided to examine the OFF-LINE task only. Both the horizontal and vertical alignment conditions were presented to the subjects. In contrast to the previous experiments, the control stimuli contained four dots, all positioned on a straight line, a condition further referred to as 0°.

Bouma (1976) and Koffka (1931) would agree in their speculations about where evidence for curvilinear interpolation is to be expected: under the 15° condition for both stimulus alignments, but not under the 0, 60, and 75° conditions.

4.1. Method

The experimental set-up was the same as in the two previous experiments, except for the following modifications: (1) a new set of eight subjects was selected from the same pool of students; (2) four new angle conditions were examined: 0, 15, 60, and 75°; (3) in one part of the experiment, the stimuli were presented in the horizontal alignment condition (as in Experiment 1), and in the other part, the alignment was vertical (as in Experiment 2). Only OFF-LINE tasks were used.

4.2. Results and conclusions

The accuracy of one subject was far worse than for the other subjects under the vertical alignment condi-

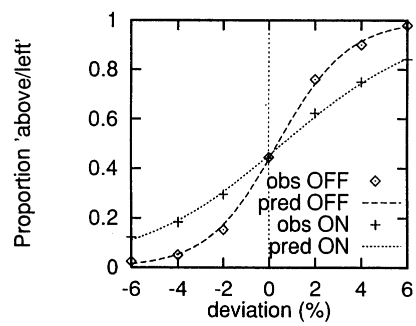

Fig. 6. Experiment 2: comparison of OFF-LINE and ON-LINE task for vertically aligned stimuli. Observed and predicted proportions responses 'left' as a function of deviation percentage of the target dot from the midpoint for both the OFF-LINE and ON-LINE task in Experiment 2, averaged over all orientation and angle conditions.

tion, and his data were replaced by those obtained from a new subject. In a latter stage, data of another subject were discarded and replaced as well: although his accuracy was rather high, his biases fluctuated wildly between experimental blocks, seemingly not as a function of the experimental conditions[3].

In what follows, first the results of the analyses of the data obtained under the vertical alignment condition are presented, followed by those obtained under the horizontal one. After comparing the results of the two conditions, the results are contrasted with those of Experiment 1 and 2.

The main result of the analyses for the vertically presented task was an effect of orientation (Model III), caused by an effect of orientation for an angle of 15° (Table 6, Fig. 7b). Hence, as expected by Bouma and Koffka, evidence was found for curvilinear interpolation under an angle of 15°, but not under 60 and 75°. However, analysing Model IV separately for each subject, only three subjects had a corresponding significant effect ($P < 0.001$) for the angle condition of 15°.

The test of Model II (Table 5) showed that there were some differences in effect of deviation in dependence upon angle. Effect of deviation was largest for the control stimuli and smallest for stimuli with an angle of 15°. Inclusion of the second order interaction did not result in an improvement of fit, for which reason it was concluded that Model IV accurately described all aspects of the data.

As expected, the orientation∗angle interaction effect under the horizontal task presentation was significant (Table 5, Model IV). This time, there was not only an effect for the angle condition of 15°, but also of 60° (Table 6). Although the effect of 75° was almost significant, analyses on the individual level showed that the effect was significant for only one subject. Hence, the results again confirm the expectations of Bouma and Koffka that curvilinear interpolation occurs for 15°, but, unexpectedly, also for the rather large angle of 60°. Both the predicted and the observed data for 15 and 60° are shown in Fig. 8.

Inspection of Table 5 leads to the conclusion that both bias and effects of Deviation are different for the various angle conditions. As for the vertically presented task, the effect of deviation was largest for the control stimuli and smallest for an angle of 75°. Again, Model IV led to an accurate description of the data because adding the second order interaction did not lead to a better fit of the data.

With the data of Experiment 3, it is possible to test within subjects whether there is a difference in accuracy

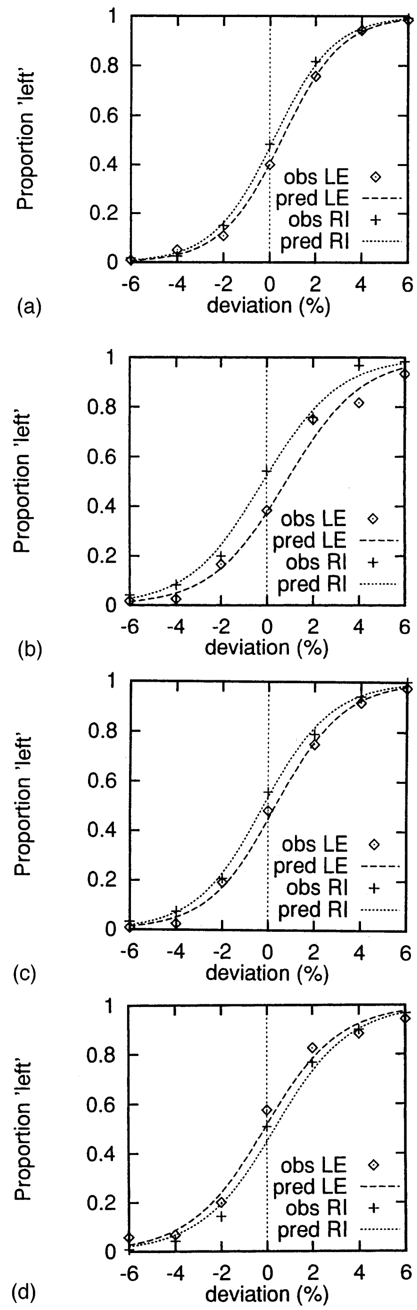

Fig. 7. Experiment 3: OFF-LINE task for vertically aligned stimuli. Observed and predicted proportions responses 'left' as a function of deviation percentage of the target dot from the midpoint for orientation 'left' and 'right' for the OFF-LINE task in Experiment 3. (a), (b), (c), (d), represent respectively, the observed and predicted proportions of angle 0, 15, 60, and 75°.

in dependence on stimulus alignment. The estimates of the general effect of deviation (Model I) amounted to 1.3066 (0.0296) for the vertical stimuli and 1.4858 (0.0346) for the horizontal ones. The difference was significant ($\chi^2_{(1)} = 15.36$, $P < 0.001$), yielding the conclusion that the differential sensitivity was somewhat higher for the horizontal stimuli. Nevertheless, Fig. 9 shows that the difference is rather small.

[3] If the data of the subject in question was not replaced by those of another one, the results in Table 6 would have shown that there was a strong negative, and thus reverse, effect for an angle of 75°, and a positive effect for the control stimulus ($P < 0.005$).

Table 5
Summary table of results of logistic regression models[a]

Model for g(D,O,α)		OFF-LINE vertical orientation	OFF-LINE horizontal orientation
Model I:	$\gamma+\beta D$	$\chi^2_{(2)}=4666.31$ (<0.0001)	$\chi^2_{(2)}=5108.69$ (<0.0001)
	Bias	$\chi^2_{(1)}=5.72$ (0.0167)	$\chi^2_{(1)}=60.66$ (<0.0001)
	Deviation	$\chi^2_{(1)}=4658.72$ (<0.0001)	$\chi^2_{(1)}=5013.18$ (<0.0001)
Model II:	$\gamma_\alpha+\beta_\alpha D$	$\chi^2_{(6)}=28.761$ (0.0001)	$\chi^2_{(6)}=132.191$ (<0.0001)
	Angle∗bias	$\chi^2_{(3)}=10.94$ (0.0121)	$\chi^2_{(3)}=95.45$ (<0.0001)
	Angle∗deviation	$\chi^2_{(3)}=17.29$ (0.0006)	$\chi^2_{(3)}=49.57$ (<0.0001)
Model III:	$\gamma_\alpha+\beta_\alpha D+\omega O$ Orientation	$\chi^2_{(1)}=9.84$ (0.0017)	$\chi^2_{(1)}=74.20$ (<0.0001)
Model IV:	$\gamma_\alpha+\beta_\alpha D+\omega_\alpha O$ Angle∗orientation	$\chi^2_{(3)}=19.45$ (0.0002)	$\chi^2_{(3)}=68.07$ (<0.0001)
Model V:	$\gamma_\alpha+\beta_{\alpha O}D+\omega_\alpha O$ Angle∗deviation∗orientation	$\chi^2_{(4)}=5.75$ (0.2186)	$\chi^2_{(4)}=5.85$ (0.2106)

[a] Subsequent rows embody increasingly complex models for explaining the data. A cell in a row contains the improvement of fit as a result of adding the variables to the explanation described in that row. Both the improvement by individual variables alone and by the variables combined are presented, together with their degrees of freedom and significance.

Combining the results of Experiment 3 with those of the other two experiments, the following conclusions on visual interpolation can be drawn:

1. Curvilinear interpolation occurs for small angles (up to 30°), regardless of the orientation of axis of symmetry.
2. Curvilinear interpolation is more pervasive under stimuli with a vertically oriented axis of symmetry (horizontal alignment) in two aspects: (a) it occurs over a larger range of angles (up to 60°); and (b) it is more salient for the small angles 15 and 30°.

The last conclusion implies that no definite answer can be stated with respect to the interpolation speculations of Bouma and Koffka without consideration of stimulus alignment. In Section 5 explanations for the alignment effects are suggested.

5. General discussion

When facing arrays of light points in an otherwise dark landscape by night, we effortlessly categorise them as ‘straight’, ‘smoothly curved’ or ‘jagged’. This fast categorisation is of vital importance since it facilitates fast and safe travelling through space in the absence of other spatial orientation carriers. Similar effortless categorisation is involved on a higher level of evolutionary relevance, such as the interpretation of individual trajectories of elementary particles in (photos of) multi-particle scatters. The Gestalt theory of visual perception recognised the importance of orientational cues — beyond proximity cues — in multi-element configurations for holistic pattern interpretation. Wertheimer (1923) coined the Law of Good Continuation to describe the perceptual interpretation of multi-element patterns on the basis of orientational cues. It remained unclear, however, exactly how the orientational information of multi-element configurations is used by a human perceiver to interpolate straight versus curved virtual lines between neighbouring elements.

Previous studies (e.g. Smits & Vos, 1987; Feldman, 1996, 1997) used template matching or pattern classification/categorisation paradigms to obtain a quantitative specification of the spatial parameters of perceived continuity in dot patterns. As it was argued in Section 1, these paradigms do presumably confound nonperceptual and perceptual origins of visual interpolation. In the present study, an experimental paradigm, called forced directional response (FDR) paradigm (Vos et al., 1997) was applied to a relative target localisation task. Unlike the paradigms in the previous studies, the combination of the FDR paradigm with the localisation tasks enabled the uncontaminated measurement of the perceptual basis of visual interpolation. The combination in question allowed us to obtain a quantitative specification of visual interpolation, inferred from differences in biases in dot localisation judgements as a function of experimental conditions. Specifically, we obtained more definite answers to the Koffka-Bouma controversy and showed that the transition from rectilinear into curvilinear interpolation is more complex

Table 6
Parameter estimates and their significance for the effect of orientation per angle (ω_α) for both the vertical and horizontal OFF-LINE task[a]

Angle	Parameter ω_α (significance)	
	OFF-LINE vertical alignment	OFF-LINE horizontal alignment
0	+0.2708 (0.0926)	−0.3108 (0.0790)
75	−0.2709 (0.0613)	+0.4326 (0.0090)
60	+0.3553 (0.0195)	+0.8243 (**0.0000**)
15	+0.6058 (**0.0000**)	+1.6139 (**0.0000**)

[a] Significance levels smaller than 0.005 are bold-faced.

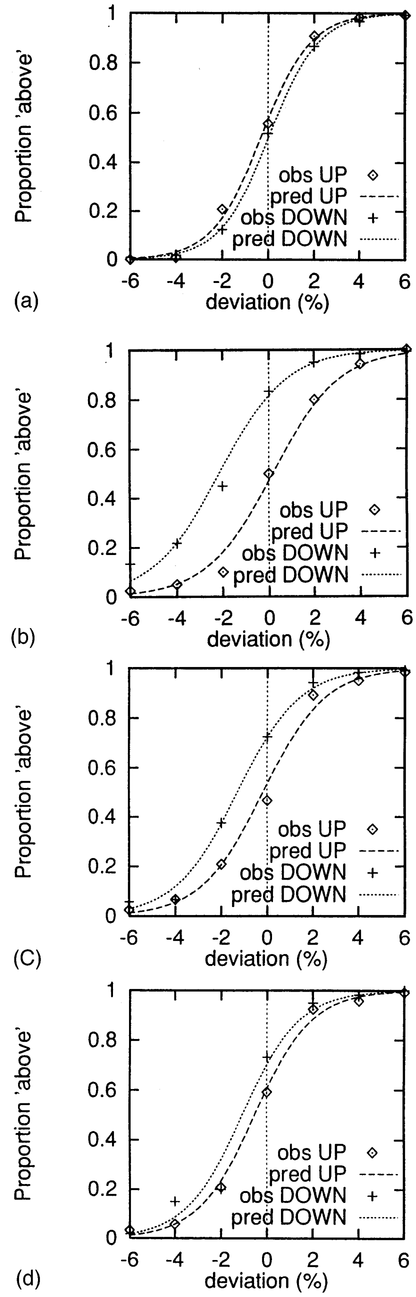

Fig. 8. Experiment 3: OFF-LINE task for horizontally aligned stimuli. Observed and predicted proportions responses 'above' as a function of deviation percentage of the target dot from the midpoint for orientation 'up' and 'down' for the OFF-LINE task in Experiment 3. (a), (b), (c), (d), represent respectively, the observed and predicted proportions of angle 0, 15, 60, and 75°.

than solely dependent on angular orientation of dots along a (virtual) contour. It was established that regular dodecagonic four-dot segments (angle of 30°) induce curvilinear interpolation, regardless of whether the alignment implies a horizontal or a vertical symmetry axis. However, in comparison to the horizontal axis condition, the vertical axis condition more strongly evokes curvilinear interpolation for relatively small angles up to 30°, and even elicits curvilinear interpolation for larger angles up to 60°. Therefore we conclude that the transition-point between both types of visual interpolation for the kind of 4-dot stimuli investigated in the present study is roughly in between 30 and 45° for the vertically aligned stimuli and in between 45 and 60° for the horizontally aligned stimuli.

One may wonder whether we did not examine the effect of more and notably finer levels of angle than those in the set (0, 15, 30, 45, 60, 75, 90) in order to establish the transition-point more precisely. We did not do so for the following reasons. First, our goal was more general in obtaining a better insight in the objective determinants of angular versus curvilinear interpolation of one-dimensional contours, by means of a new psychophysical paradigm which avoids disadvantages of classical paradigms. Second, we believe that the search for more precise transition points than reported in the last paragraph is not fruitful for the following reason. In spite of the highly significant differences between the response trends for the two stimulus alignments, all experiments demonstrated that there are substantial differences between subjects with respect to the angle effect on interpolation for each alignment. These differences between subjects suggest that one general, subject-invariant, transition-point does not exist and that it could be difficult to find a more precise answer than formulated in the previous paragraph.

Apart from evidence with respect to the hypothesis of curvilinear versus rectilinear visual interpolation, the three experiments yielded other interesting phenomena of the visual system in relation to the tasks. More specifically, in Experiment 3 it was found that the subjects' achievements in the OFF-LINE task with horizontally aligned stimuli (vertical symmetry axis) were superior to those obtained with the complementary task (vertically aligned stimuli; horizontal symmetry axis). Additionally, the first two experiments demonstrated that the ON-LINE task was much more difficult than the OFF-LINE task. Finally, the results

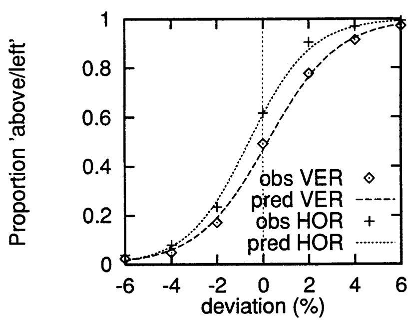

Fig. 9. Experiment 3: comparison of OFF-LINE tasks for vertically aligned stimuli and for horizontally aligned stimuli. Observed and predicted proportions responses 'left' (vertical alignment) and 'above' (horizontal alignment) as a function of deviation percentage of the target dot from the midpoint for both OFF-LINE tasks in Experiment 3, averaged over all orientation and angle conditions.

of the first two experiments indicated that the ON-LINE task was most difficult when the stimuli were presented vertically. In the following paragraphs, preliminary explanations are suggested for the three phenomena, to begin with the comparison of the OFF-LINE with the ON-LINE tasks.

Possible explanations of the relative difficulty of the ON-LINE tasks are offered by an analysis of the task requirements. The OFF-LINE task required a subject to detect only the sign of a deviation from a virtual line between the reference dots. Subjects could solve the ON-LINE task in two ways. One strategy is to compare the two distances of the target dot with each of the reference dots. The direction of the deviation is then indicated by the reference dot to which the distance is smallest. Following another possible strategy, a correct response in the ON-LINE task is obtained by detecting deviation of the target from an induced axis of symmetry in the stimulus. Of course, a subject could, consciously or unconsciously, combine the two strategies. They are more demanding than the strategy to be applied in the OFF-LINE task: comparing distances is more a cognitive task than a perceptual one, and inducing a line through two dots is presumably a more easy and stable process than inducing a symmetry axis that does not pass through stimulus dots.

A tentative conclusion about the plausibility of the two alternative ON-LINE strategies is obtained by comparing subjects' achievements for both ON-LINE tasks. Achievements were best under a vertical symmetry axis condition. If the subject only compared the two distances, then no effects of stimulus alignment would have been expected. However, the fact that the ON-LINE task was more difficult under a horizontal axis of symmetry is in agreement with the previously reported finding that detection of deviation from left-right symmetry is superior to that for stimuli endowed with horizontal symmetry (e.g. Barlow & Reeves, 1979; Jenkins, 1983; Zimmer, 1984; Dakin & Hess, 1997; Wenderoth, 1997; see Wagemans, 1995, for a review). Therefore, the results suggest that the subject at least partly makes use of information concerning the symmetry of the stimuli.

Surprisingly, Experiment 3 demonstrated that subjects' differential sensitivity was higher for the horizontally aligned stimuli than for the vertically aligned stimuli. This result suggests that deviations from a horizontal illusory line are less difficult to detect than deviations from a vertical illusory line. Studies on orientational anisotropy in the visual system using different tasks and methods (see Jenkins, 1985) report differences in sensitivity between horizontal and vertical orientations on the one hand and oblique orientations on the other hand, with the visual system being less sensitive to the latter. The latter difference is widely accepted and is called the *oblique effect*. Sensitivity differences between horizontal and vertical orientations are not reported. How can we explain the difference between the two orientations in our study? First, note that the difference was relatively small but significant with the enormous number of datapoints (13440). Other studies had less data and were unlikely to demonstrate a small sensitivity difference between the two orientations. Assuming the difference, albeit small, is real, it can be accounted for by anisotropies at the early level of visual processing or at higher levels. At the cortical level (1) there could be more horizontal units than vertical ones; (2) horizontal units could be more sensitive than vertical ones; or (3) receptive fields of horizontal units could be longer than those of vertical units. Differences at the cortical level with respect to all three variables have been demonstrated to (at least partially) explain the oblique effect (e.g. (1) Mansfield, 1974; (2) Appelle, 1972; (3) Jenkins, 1985). Early studies (e.g. Polyak, 1941) suggested that there is no difference in density of receptors between the vertical and horizontal meridians, making the first explanation unlikely.

Studies on the oblique effect also demonstrated that higher order levels of visual processing have an effect on orientation perception. For example, Vogels and Orban (1985) found that practice partially eliminates the oblique effect. Practice can also explain the difference in sensitivity between horizontal and vertical orientations, because the horizontal is important in (learning) reading and writing. Other evidence for the relevance of higher level visual processing is obtained by Herbert and Humprey (1996), who found that the corpus callosum mediates a left–right symmetry advantage. Subjects born without a corpus callosum did not detect left–right symmetry at fixation more easily than symmetry at other orientations like usual subjects did. The latter result suggests that higher sensitivity for horizontally aligned stimuli is the result of optimal integration of the stimulus via the corpus callosum when vertically symmetric stimuli are presented bilaterally.

Although we expected effects of angle on curvilinear interpolation, we certainly did not expect a difference in this effect for horizontally and vertically aligned stimuli. We found no evidence or hints about differences in curvilinear interpolation for the two orientations in the literature, and conclude that our study may be the first that reports these differences. Their explanation of these differences may be sought in properties of the visual system at lower or higher levels of processing as discussed above. It could be that there are relatively more functional units responding to illusory curvilinear contours than to illusory rectilinear contours for horizontal contours in comparison to vertical contours. Alternatively, the units for detecting illusory horizontal curvilinear contours could be more sensitive or have longer receptive fields than the units for illusory vertical curvilinear contours. At a higher level of visual processing, more curvilinear interpolation for horizontal alignments can be explained if curvilinear interpolation is facilitated by parallel processing of both hemispheres and/or the corpus callosum. Parallel processing and the corpus callosum might induce a relatively strong coherence of all pattern constituents, which in the case of our stimuli could result in a higher likelihood of effects of (symmetric) context dots on the performance in the target localisation task and, possibly, curvilinear interpolation. The explanation suggested here is speculative however, and more research is necessary to provide a satisfactory explanation of the phenomenon.

Another relevant point of discussion is a methodological one, namely the (dis)advantages of the blocked design, applied in all three experiments. That is, each of the 16 blocks consisted of stimuli which were similar with respect to all independent variables except for the degree of deviation of the target dot. The advantage is that subjects were prevented from distraction by continuous displacements of context dots over trials, which would have been the case with a mixed design procedure. The blocked design entails a disadvantage as well. If, for whatever reason other than experimental manipulation, the subject's inclination to respond to one of the two response categories varies over blocks, then the variation is incorporated in the estimated effects of angle and orientation[4]. If these effects were present in our experiments, then they were probably cancelled out because eight subjects were involved in each experiment and because a Latin-square design was used in the experiments.

A mixed design would automatically control for a variation in response bias because each block of stimuli would contain the same number of stimuli of each orientation∗angle condition. To check whether the choice of design had influence on the results, a fourth and replicative experiment seemed warranted, with a mixed instead of a blocked design. Because the results with respect to the effects of interest were similar to those obtained for the three other experiments, we describe the experiment only in the present section.

Experiment 4 consisted of ten blocks of each 168 stimuli. Within a block, all stimuli had the same alignment (vertical or horizontal), but differed in angle (four levels) and orientation (two levels). For each angle∗orientation condition, 21 stimuli were presented, each of the seven levels of deviation presented three times. Only the small angle conditions were examined, that is angles of 0, 15, 30, and 45°. Again, eight new subjects participated in the experiment. The results confirmed our expectation that the effect of deviation in a mixed design is smaller than for a blocked design, probably so because of the distraction due to the apparently moving context dots over trials. Because evidence for curvilinear interpolation was also found in Experiment 4 with a mixed design, we have confidence in the validity and generalisability of the results obtained with the first three experiments.

Our aim was to obtain insight in the determinants of angular versus curvilinear interpolation of 1-dimensional contours. It remains to be investigated to what extent the conclusions of the present study about visual interpolation can be generalised to more complex dot stimuli, and whether they are invariant under stimulus scale transformations. Stimulus complexity can be increased in several ways. One way is to construct dot polygon segments endowed with non-circular more complex contours, e.g. 'worm' like contours (Feldman, 1996). A second would be to use more dots in a stimulus on the underlying contour. Varying inter-dot distances along the contour of the stimuli might also provide additional insights in the determinants of visual interpolation (Feldman, 1997). It is not self-evident what the effect of combinations of variations with respect to type of curvature, nonequidistance, and dot numerosity will be on the visual interpolation. Further research of those effects is warranted and is on our future research agenda. A study of the effect of scale of the stimulus seems justified as well, since curvature, expressed as the second derivative of the contour, is inversely related to the scale of a stimulus. Because of the promising results of our study, the authors recommend using the psychophysical paradigm used in this study in favour of the more traditional methods in investigating the effects of the variables mentioned in this paragraph.

[4] Note that the data of one subject were discarded because of his large variation in response bias over conditions.

References

Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: the 'oblique effect' in man and animals. *Psychological Bulletin*, *78*, 266–278.

Barlow, H. B., & Reeves, B. C. (1979). The versatility and absolute efficiency of detecting mirror symmetry in random dot displays. *Vision Research*, *19*(7), 783–793.

Beardslee, D. C., & Wertheimer, M. (1958). *Readings in perception*. New York: D. Van Nostrand.

Bornstein, M. H., & Styles-Davis, J. (1984). Discrimination and memory for symmetry in young children. *Developmental Psychology*, *20*, 637–649.

Bouma, H. (1976). Perceptual functions. In J. A. Michon, E. G. Eijkman, & L. F. de Klerk, *Dutch handbook of psychonomy* (pp. 229–287). Deventer, Netherlands: Van Loghem Slaterus (in Dutch).

Caelli, T., & Umansky, J. (1976). Interpolation in the visual system. *Vision Research*, *16*, 1055–1060.

Compton, B. J., & Logan, G. D. (1993). Evaluating a computational model of perceptual grouping by proximity. *Perception and Psychophysics*, *53*, 403–421.

Dakin, S. C., & Hess, R. F. (1997). The spatial mechanisms mediating symmetry perception. *Vision Research*, *37*(20), 2915–2930.

Ellis, W. D. (1938). *A source book of Gestalt psychology*. London: Routledge and Kegan Paul.

Feldman, J. (1996). Regularity vs genericity in the perception of collinearity. *Perception*, *25*, 335–342.

Feldman, J. (1997). Curvilinearity, covariance, and regularity in perceptual groups. *Vision Research*, *37*, 2835–2848.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Hochberg, J. (1981). Levels of perceptual organization. In M. Kubovy, & J. R. Pomerantz, *Perceptual organization* (pp. 255–279). Hillsdale, NJ: Erlbaum.

Hosmer, D. W., & Lemeshow, S. (1989). *Applied logistic regression*. New York: Wiley.

Herbert, A. M., & Humprey, G. K. (1996). Bilateral symmetry detection: testing a 'callosal' hypothesis. *Perception*, *25*, 463–480.

Jenkins, B. (1983). Component processes in the perception of bilaterally symmetric dot textures. *Perception and Psychophysics*, *34*, 433–440.

Jenkins, B. (1985). Orientational anisotropy in the human visual system. *Perception and Psychophysics*, *37*(2), 125–134.

Kleinbaum, D. G. (1994). *Logistic regression*. New York: Springer.

Koffka, K. (1931). Psychology of visual perception. In A. Bethe, *Handbook of normal and pathological physiology* (pp. 1215–1271). Berlin: Dessoir (in German).

Kubovy, M., & Wagemans, J. (1995). Grouping by proximity and multistability in dot patterns. *Psychological Science*, *6*, 225–234.

Link, N. K., & Zucker, S. W. (1987). Sensitivity to corners in flow patterns. *Spatial Vision*, *2*, 233–244.

Luce, R. D. (1959). On the possible psychophysical laws. *Psychological Review*, *66*, 81–95.

Luce, R. D. (1963). A threshold theory for simple detection experiments. *Psychological Rerview*, *70*, 61–79.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: a user's guide*. Cambridge: Cambridge University Press.

Mansfield, R. J. W. (1974). Neural basis of orientation perception in primate vision. *Science*, *186*, 1133–1135.

Palmer, S. E., & Hemenway, K. (1978). Orientation and symmetry: effects of multiple, rotational, and near symmetries. *Journal of Experimental Psychology*: *Human Perception and Performance*, *4*, 691–702.

Parent, P., & Zucker, S. W. (1989). Trace inference, curvature consistency, and curve detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *11*, 823–839.

Pizlo, Z., Salach-Golyska, & Rosenfeld, A. (1997). Curve detection in a noisy image. *Vision Research*, *37* (9) 1217–1241.

Polyak, S. L. (1941). *The retina*. Chicago: University Chicago Press.

Smits, J. T., & Vos, P. G. (1986). A model for the perception of curves in dot figures: the role of local salience of 'virtual lines'. *Biological Cybernetics*, *54*, 407–416.

Smits, J. T., & Vos, P. G. (1987). The perception of continuous curves in dot stimuli. *Perception*, *16*, 121–131.

Tyler, C. W. (1996). Human symmetry perception. In C. W. Tyler, *Human symmetry perception and its computational analysis* (pp. 3–25). Utrecht, Netherlands: VSP.

Van Oeffelen, M. P., & Vos, P. G. (1982). Configurational effects on the enumeration of dots: counting by groups. *Memory and Cognition*, *10*, 396–404.

Van Oeffelen, M. P., & Vos, P. G. (1983). An algorithm for pattern description on the level of relative proximity. *Pattern Recognition*, *16*, 341–348.

Vogels, R., & Orban, G. A. (1985). The effect of practice on the oblique effect in line orientation judgments. *Vision Research*, *25*(11), 1679–1687.

Von Helmholtz, H. (1962). In J. P. Southall, *Treatise on physiological optics*, *vol. 3*. New York: Dover (J. P. Southall, Trans.; originally work published 1856, in German).

Vos, P. G., & Helsper, E. L. (1991). Modelling linear structure in dot patterns. In I. Dvorak, & A. V. Holden, *Mathematical approaches to brain functioning diagnostics* (pp. 429–441). Manchester: Manchester University Press.

Vos, P. G., Van Assen, M. A., & Franek, M. (1997). Perceived tempo change is dependent on base tempo and direction of change: evidence for a generalized version of Schulze's (1978) internal beat model. *Psychological Research*, *59*, 240–247.

Wagemans, J. (1995). Detection of visual symmetries. *Spatial Vision*, *9*, 9–32.

Wenderoth, P. (1994). The salience of vertical symmetry. *Perception*, *23*, 221–236.

Wenderoth, P. (1997). The effects on bilateral-symmetry detection of multiple symmetry, near symmetry, and axis orientation. *Perception*, *26*, 891–904.

Wertheimer, M. (1921). Untersuchungen zur Lehre von der Gestalt I Prinzipielle Bemerkungen. (Investigations into Gestalt theory I Basic considerations). *Psychologische Forschung*, *1*, 47–58.

Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt II. (Investigations into Gestalt theory II). *Psychologische Forschung*, *4*, 301–350.

Zimmer, A. C. (1984). Foundations for the measurement of phenomenal symmetry. *Gestalt Theory*, *6*, 118–157.

Zucker, S. W. (1984). Early orientation selection and grouping: type I and type II processes. In T. M. Caelli, & P. C. Dodwell, *Figural synthesis*. Hillsdale, NJ: Erlbaum.

Zucker, S. W. (1986). The computational connection in vision: early orientation selection. *Behaviour Research Methods*, *Instruments and Computers*, *18*, 608–617.

Zucker, S. W., Dobbins, A., & Iverson, L. (1989). Two stages of curve detection suggest two styles of visual computation. *Neural Computation*, *1*, 68–81.